Physics of a long and very long baseline neutrino program

MILIND DIWAN
Brookhaven National Laboratory
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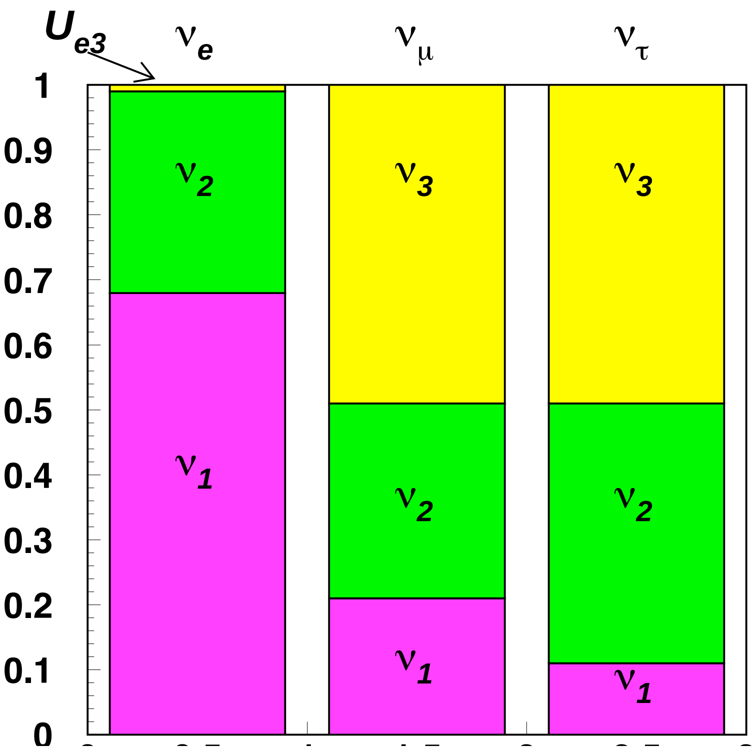
Prologue

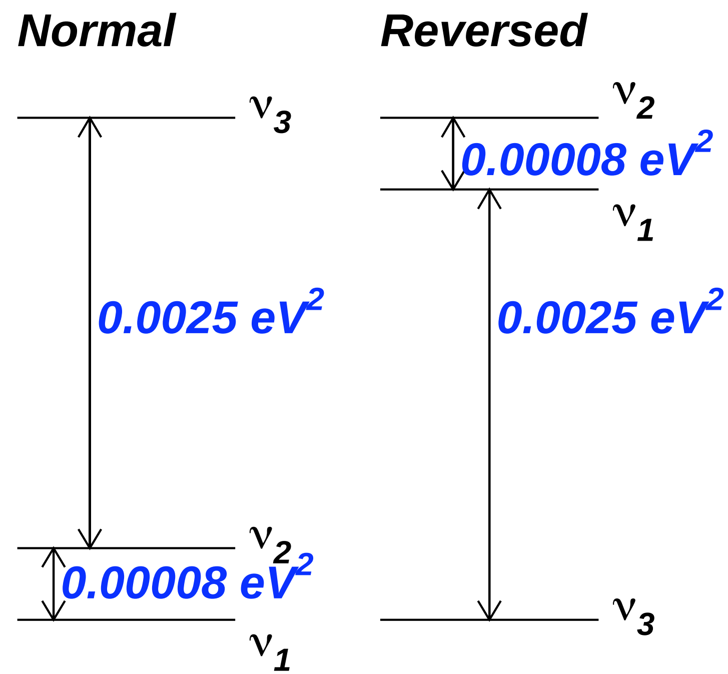
- Neutrino oscillations have emerged as a key topic that requires new intense high energy proton source.
- There is general agreement on the need for a source with Ep ~ 20-80 GeV.
- Power level is determined by the need for event rate. General agreement ~1-2 MW as first phase.
- In this I will focus on the physics case and two possible alternatives. I will also describe the FNAL/ BNL joint study to develop the next phase of this program. Please join this study.

Apologies

- Japanese program will be covered in third talk.
- There is an international scoping study (ISS) in progress focussed on muon storage ring based ideas.
- My focus on conventional beams only.
- First part of talk should be general about the physics, but I will not talk about the LSND problem.

3 Generation oscillations





Difference in mass squares: $(m_2^2 - m_1^2)$

2-nu: $$P(\nu_a \to \nu_b) = \sin^2 2\theta \sin^2 \frac{1.27((m_2^2 - m_1^2)/eV^2)(L/km)}{(E/GeV)}$$

3-nu: CP phase

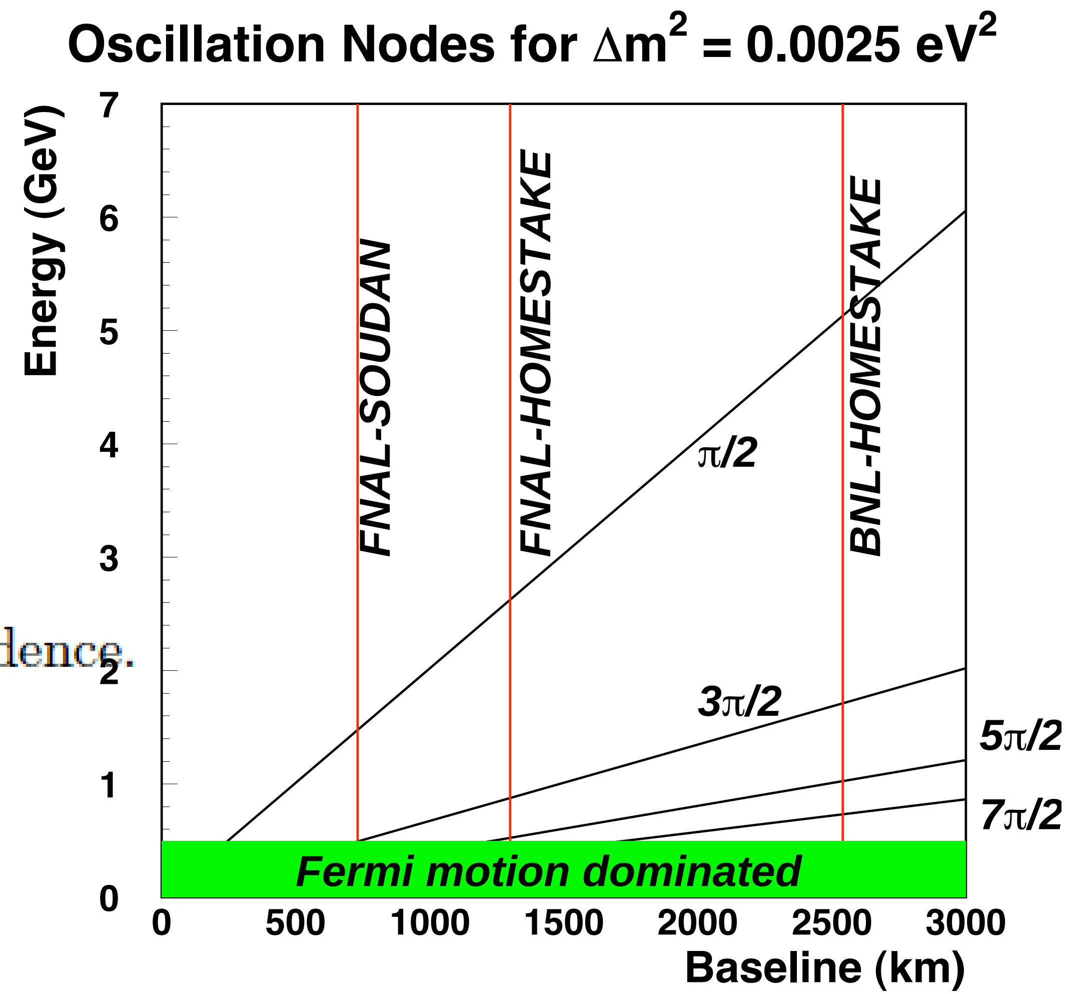
$$\begin{aligned} P(\nu_a \to \nu_b) &= \textstyle\sum_i |U_{ai}|^2 |U_{bi}|^2 \\ &+2Re(U_{a1}^* U_{b1} U_{a2} U_{b2}^* \times exp(-i\Delta m_{21}^2 L/2E) \\ &+2Re(U_{a1}^* U_{b1} U_{a3} U_{b3}^* \times exp(-i\Delta m_{31}^2 L/2E) \\ &+2Re(U_{a2}^* U_{b2} U_{a3} U_{b3}^* \times exp(-i\Delta m_{32}^2 L/2E) \end{aligned}$$

no matter effects

Oscillation nodes at $\pi/2, 3\pi/2, 5\pi/2, \ldots$ $(\pi/2)$: $\Delta m^2 = 0.0025eV^2$, $E = 1GeV$, $L = 494km$.

Solar : L~15000km

Physics and Oscillation Nodes



First Generation

- Focus on first node oscillations.
- Sensitivity for θ_{13}.

Next Generation

- Observe multiple nodes
  For precision and reduce flux dependence.
  Better sensitivity to θ_{13}.
- Longer flight paths:
  Larger matter effects for hierarchy resolution and new physics.
- Better S/B for CP violation (δ_{CP}) measurement.
  Flux $\sim L^{-2}$, but CP asymmetry $\sim L$; sensitivity to CPV independent of L. (Marciano hep-ph/0108181).

$\nu_\mu \to \nu_e$ with matter effect

Approximate formula (M. Freund)

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\frac{\sin^2 2\theta_{13}}{(\hat{A}-1)^2}\sin^2((\hat{A}-1)\Delta)$$

~7500 km
no CPV.
magic bln

$$+\alpha\frac{8J_{CP}}{\hat{A}(1-\hat{A})}\sin(\Delta)\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)$$

CPV term
approximate
dependence
~L/E

$$+\alpha\frac{8I_{CP}}{\hat{A}(1-\hat{A})}\cos(\Delta)\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)$$

$$+\alpha^2\frac{\cos^2\theta_{23}\sin^2 2\theta_{12}}{\hat{A}^2}\sin^2(\hat{A}\Delta)$$

solar term

linear dep.

$J_{CP} = 1/8\sin\delta_{CP}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}$

$I_{CP} = 1/8\cos\delta_{CP}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}$

$\alpha = \Delta m^2_{21}/\Delta m^2_{31}$, $\Delta = \Delta m^2_{31}L/4E$

$\hat{A} = 2VE/\Delta m^2_{31} \approx (E_\nu/GeV)/11$ For Earth's crust.

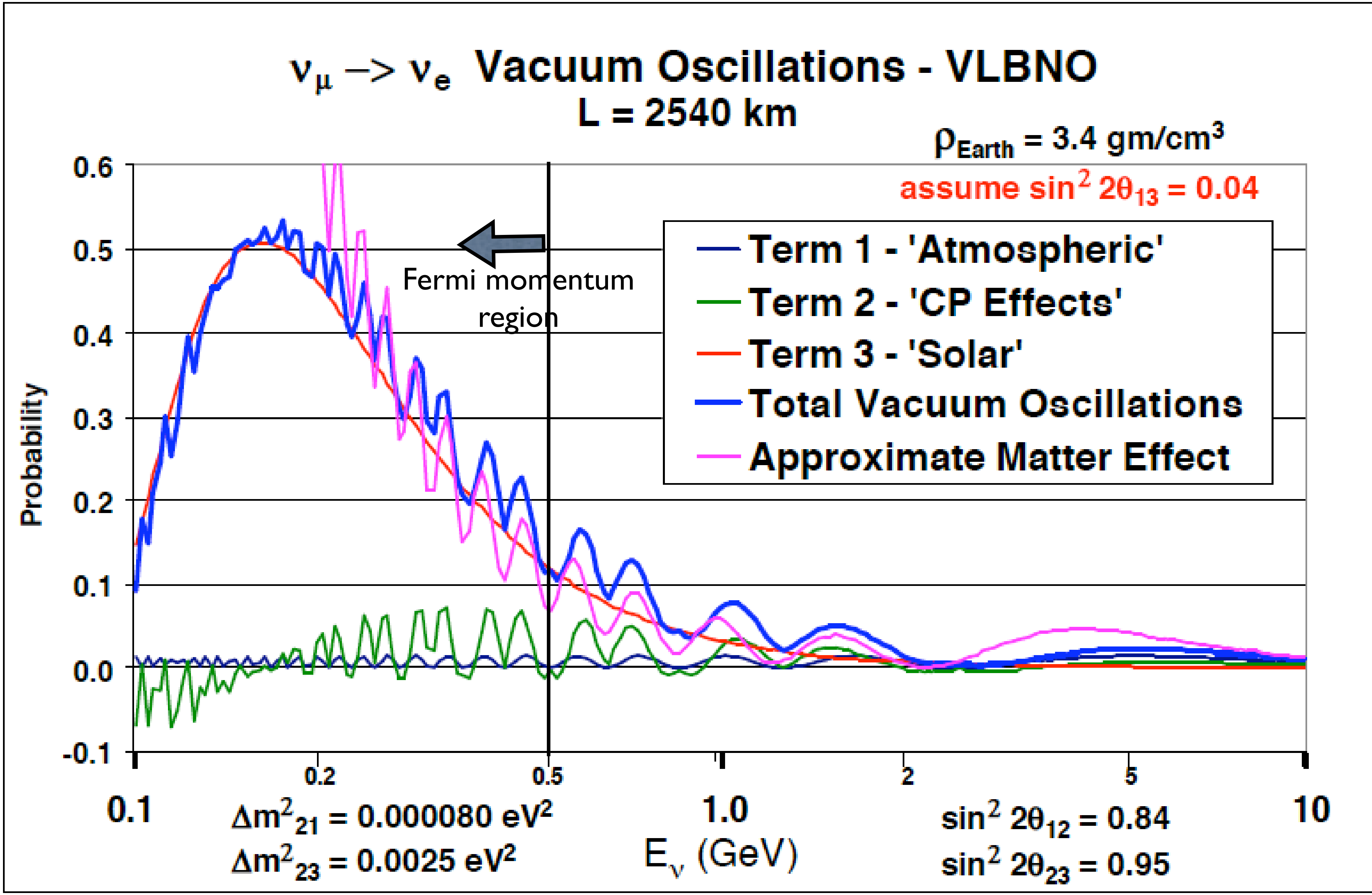
Comments about matter effect

$V = \sqrt{2} G_F n_e$. n_e is the density of electrons in the Earth.

$\hat{A} = \approx 7.6 \times 10^{-5} \times (D/gm/cm^3) \times (E_\nu/GeV)/(\Delta m^2_{31}/eV^2)$,

Also recall $\Delta m^2_{31} = \Delta m^2_{32} + \Delta m^2_{21}$.

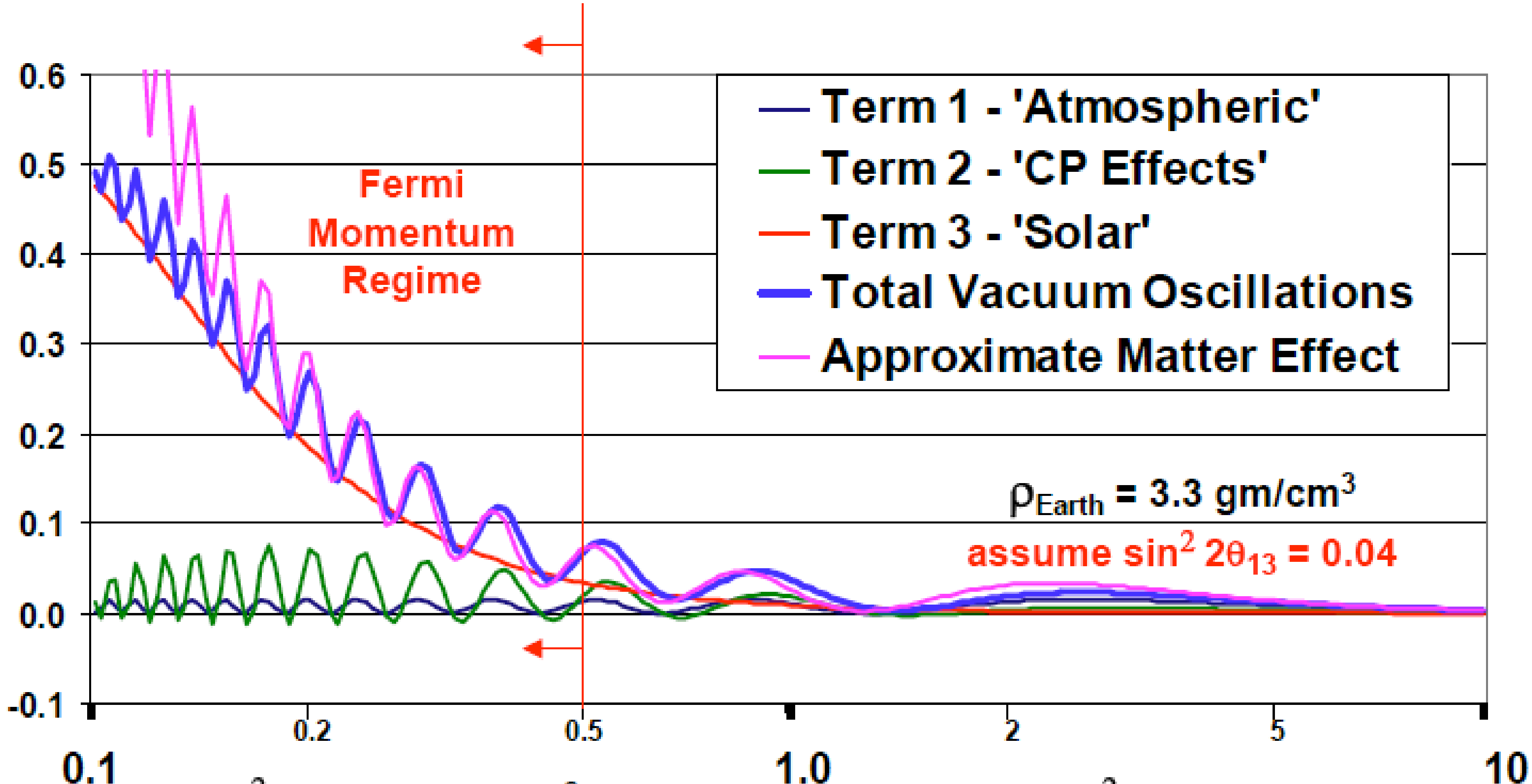
- This is a very approximate equation, not applicable below the first maximum.
- First term has the effect of $\sin^2 2\theta_{13}$ and matter.
- Second and third terms have effects of CP.
- Term with J_{CP} changes sign for $(Anti - \nu_\mu) \rightarrow (Anti - \nu_e)$
- Last term is almost independent of Δm^2_{31} and is purely dominated by the solar Δm^2_{21}



$\nu_\mu \to \nu_e$ Vacuum Oscillations - VLBNO
L = 2540 km
ρ_{Earth} = 3.4 gm/cm^3
assume $\sin^2 2\theta_{13}$ = 0.04
Fermi momentum region
Term 1 - 'Atmospheric'
Term 2 - 'CP Effects'
Term 3 - 'Solar'
Total Vacuum Oscillations
Approximate Matter Effect
Probability
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
0.1
0.2
0.5
1.0
2
5
10
Δm^2_{21} = 0.000080 eV^2
Δm^2_{23} = 0.0025 eV^2
E_ν (GeV)
$\sin^2 2\theta_{12}$ = 0.84
$\sin^2 2\theta_{23}$ = 0.95

$\nu_\mu \rightarrow \nu_e$ Vacuum Oscill. - VLBNO

L = 1300 km – FNAL to Homestake



$\Delta m^2_{21} = 0.000080\ eV^2$

$\Delta m^2_{23} = 0.0025\ eV^2$

$\sin^2 2\theta_{12} = 0.84$

$\sin^2 2\theta_{23} = 0.95$

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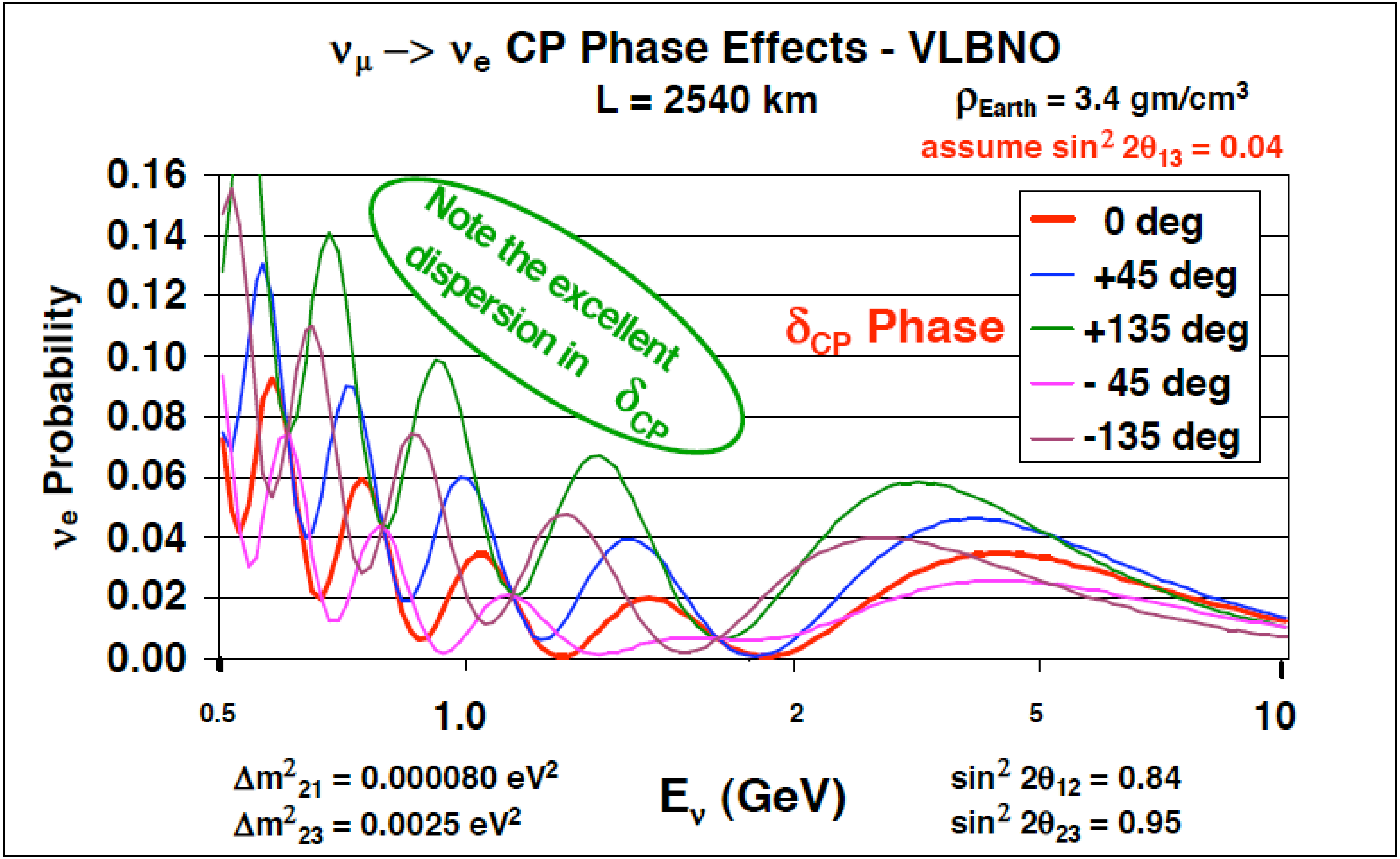
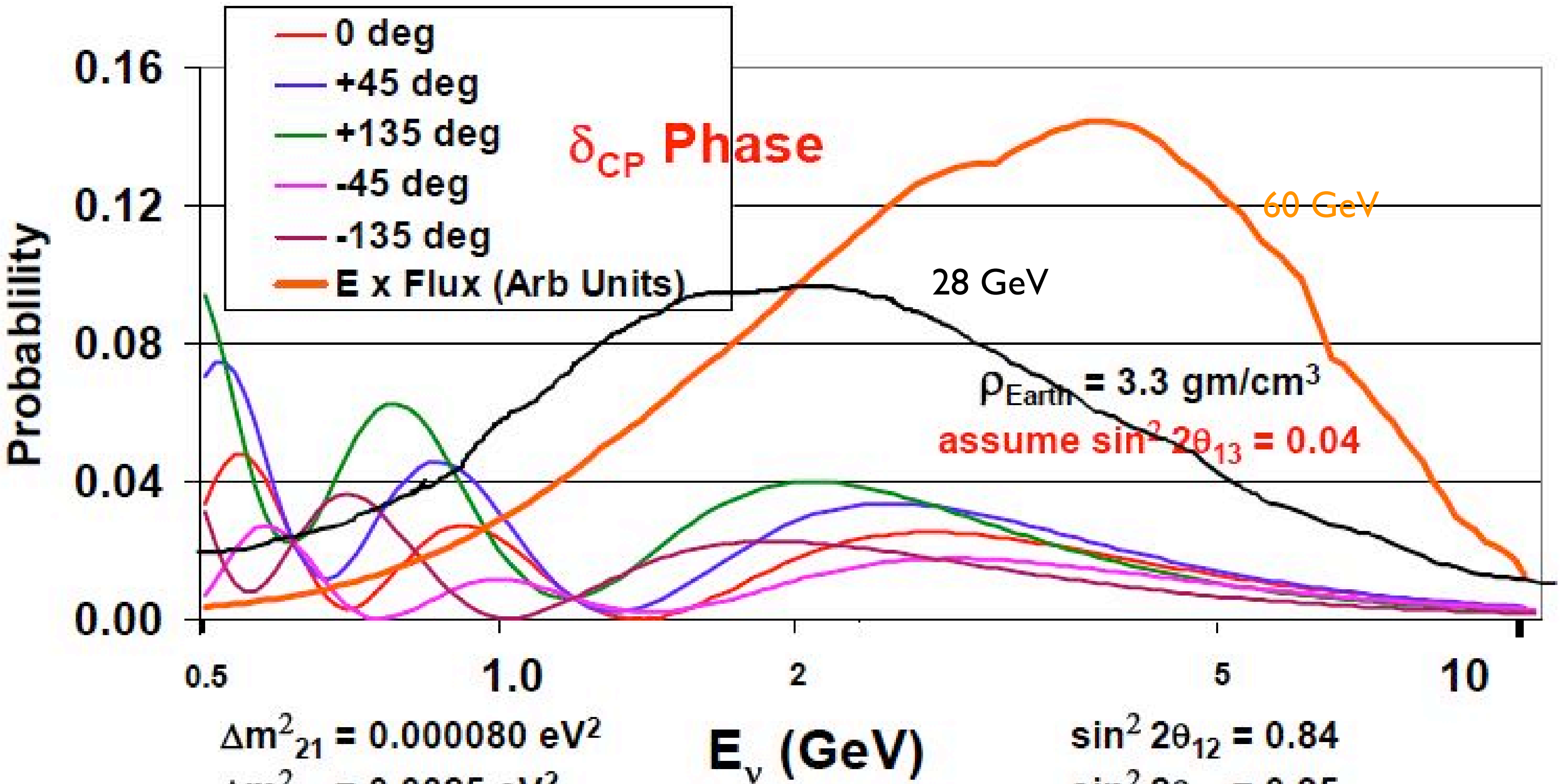


$\nu_\mu \rightarrow \nu_e$ CP Phase Effects - VLBNO
L = 2540 km
ρ_{Earth} = 3.4 gm/cm^3
assume $\sin^2 2\theta_{13} = 0.04$
Note the excellent dispersion in δ_{CP}
δ_{CP} Phase
0 deg
+45 deg
+135 deg
- 45 deg
-135 deg
ν_e Probability
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0.5
1.0
2
5
10
E_ν (GeV)
$\Delta m^2_{21} = 0.000080$ eV^2
$\Delta m^2_{23} = 0.0025$ eV^2
$\sin^2 2\theta_{12} = 0.84$
$\sin^2 2\theta_{23} = 0.95$

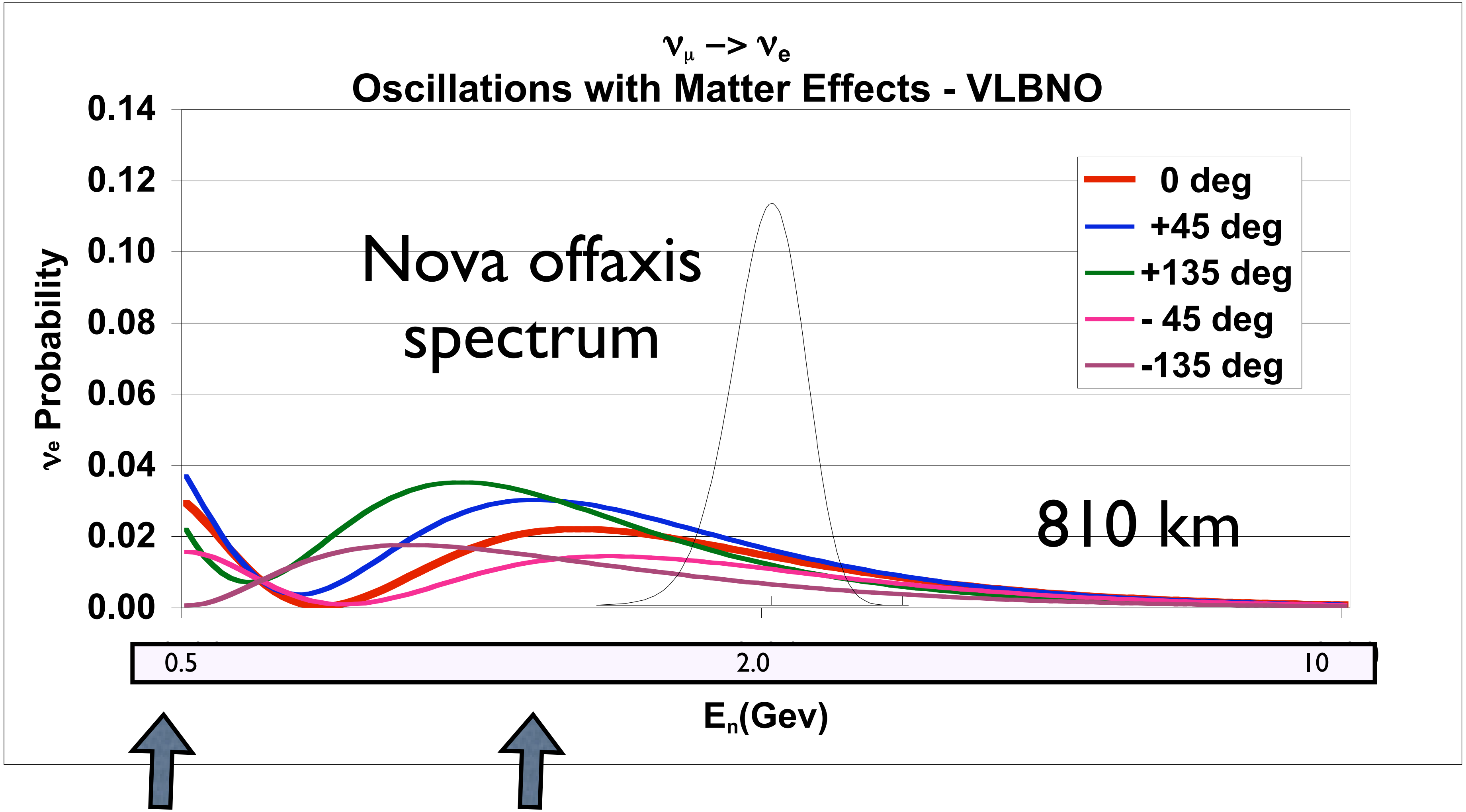
$\nu_\mu \rightarrow \nu_e$ CP Phase Effects - VLBNO

L = 1300 km – FNAL to Homestake



$\Delta m^2_{21} = 0.000080\ eV^2$
$\Delta m^2_{23} = 0.0025\ eV^2$

$\sin^2 2\theta_{12} = 0.84$
$\sin^2 2\theta_{23} = 0.95$



second max
~0.5GeV

first max
~1.5 GeV

Same parameters as before

Observations

- Sensitivity to CP is independent of distance after ~1000km
- Short baseline = high statistics, small effects.
  Longer baseline = bigger effects, small statistics
- The size of detectors and beam power needed does not depend on theta_13 (as long as it is not very small, S. Parke)
- Two narrow band experiments could observe the signal with different strengths; need to examine ambiguities.
- The "solar" term could be observed with large L/E.
- For the future we need a low energy broad band beam.
  Must have ~4m wide tunnel. I have assumed 200 m length.
  Low energy horn also (with target deep inside)

Two approaches

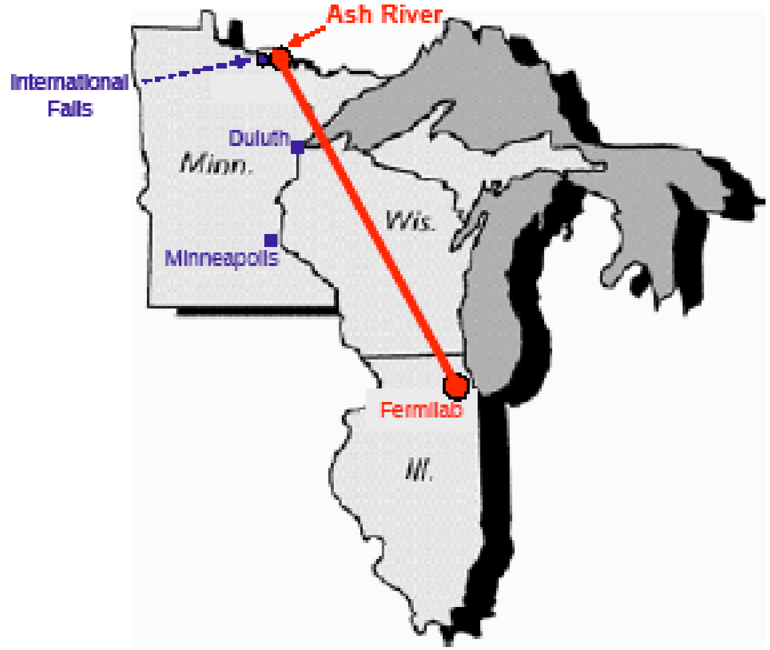
No new beam, but restricted physics because of surface det.

- Off axis: Use existing NUMI beam. NOvA(25kT) will be built ~10mrad offaxis for the first maximum. NOvA2(50kT LAR) will be built at 40 mrad for second maximum. Both detectors will be on the surface. Combine the results to extract th13, mass hierarchy, and CPV.

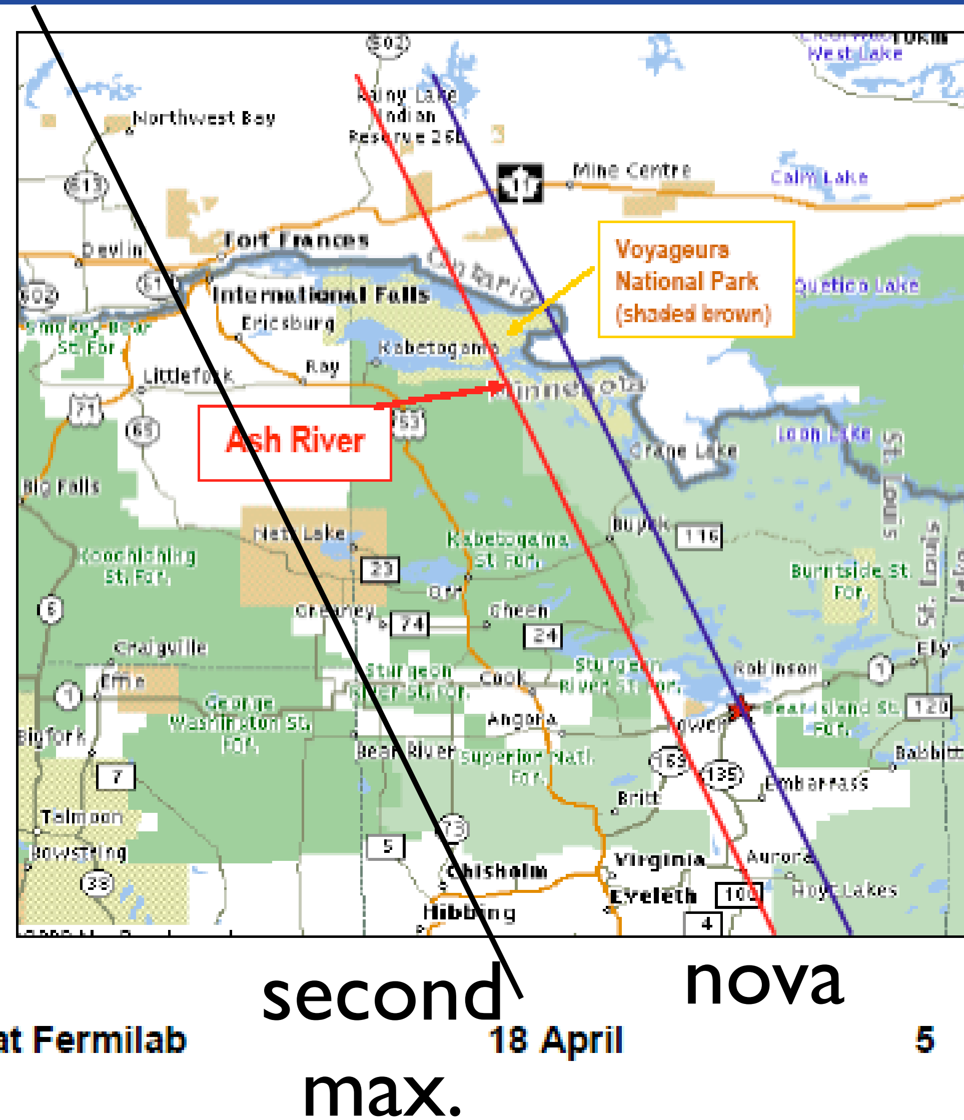
New beam, but detector capable of Nucleon Decay

- Low energy wide band: Couple the long baseline program to a new deep underground laboratory (DUSEL). Site a large detector (~200kT if water Cherenkov) at approximately 5000 mwe. Build a new wide beam with a spectrum shaped to be optimum (0.5-6 GeV). Use detector resolution to extract multiple nodes.

- Concerns: event rate, NC background, resolution, parameter sensitivity, total cost and timeliness.



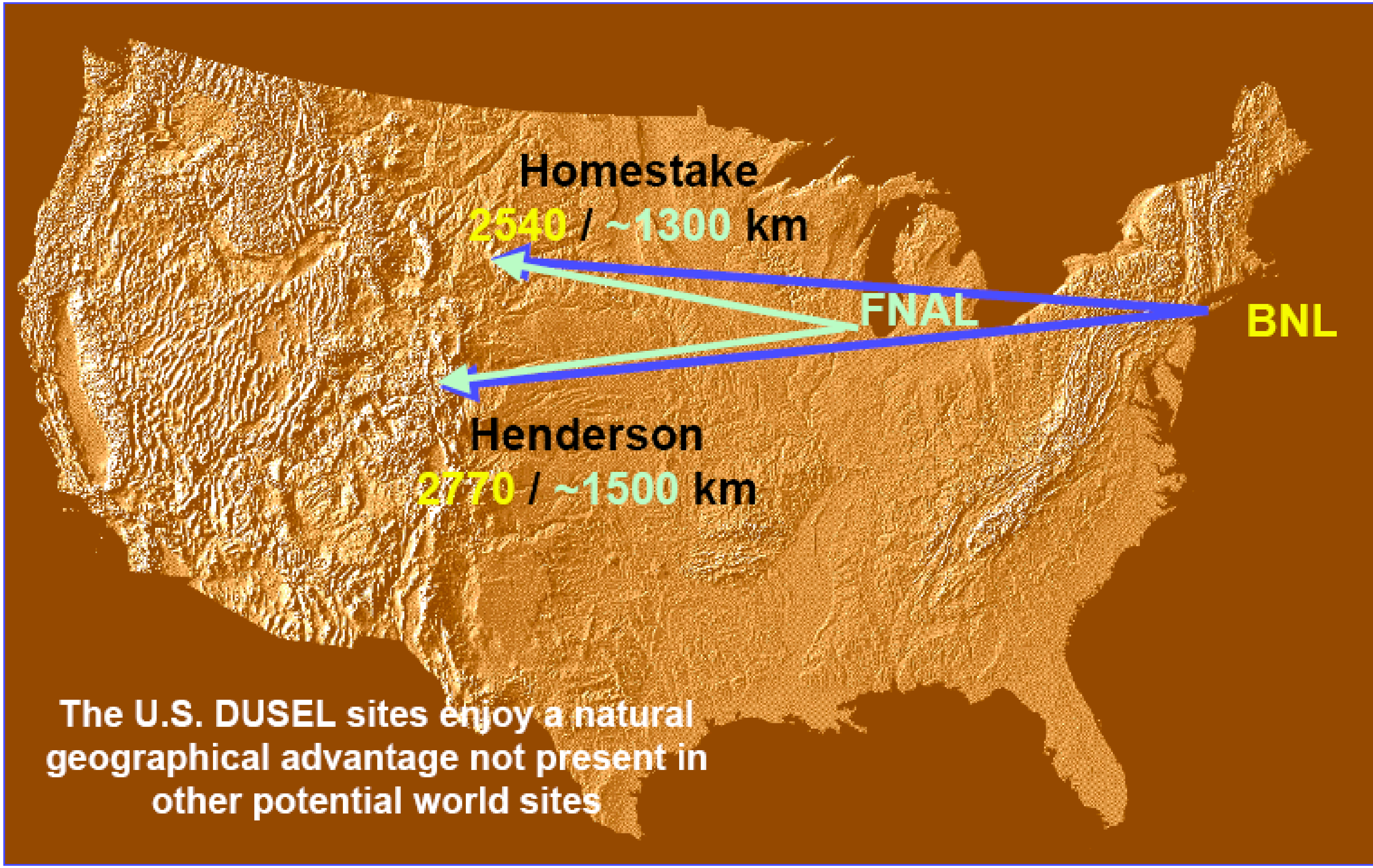
The Ash River site is the furthest available site from Fermilab along the NuMI beamline. This maximizes NOvA's sensitivity to the mass ordering.



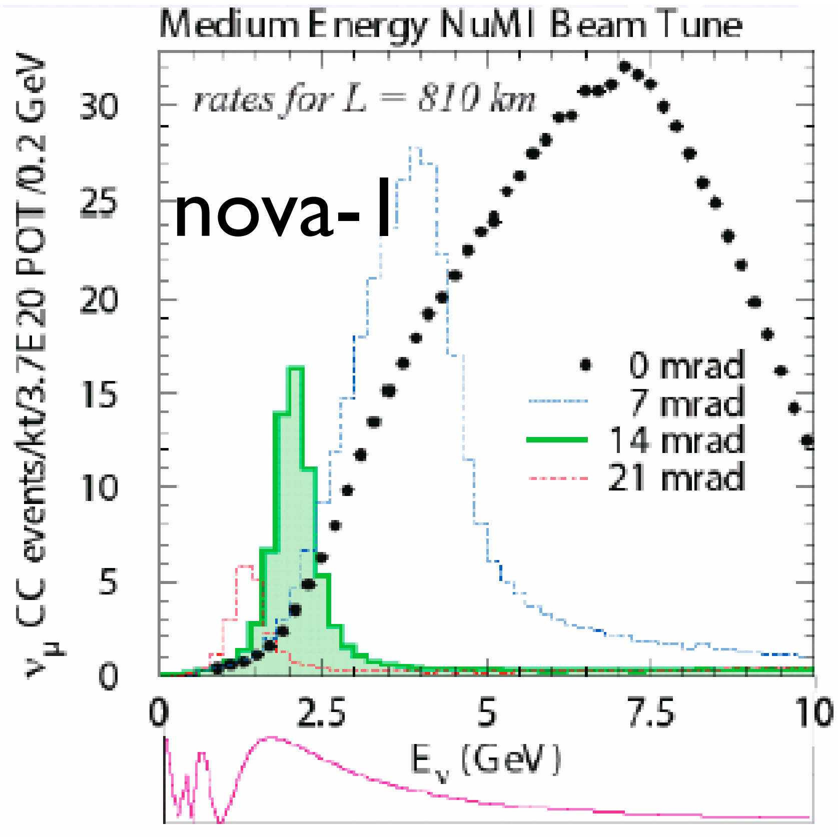
Gary Feldman P5 at Fermilab 18 April 5

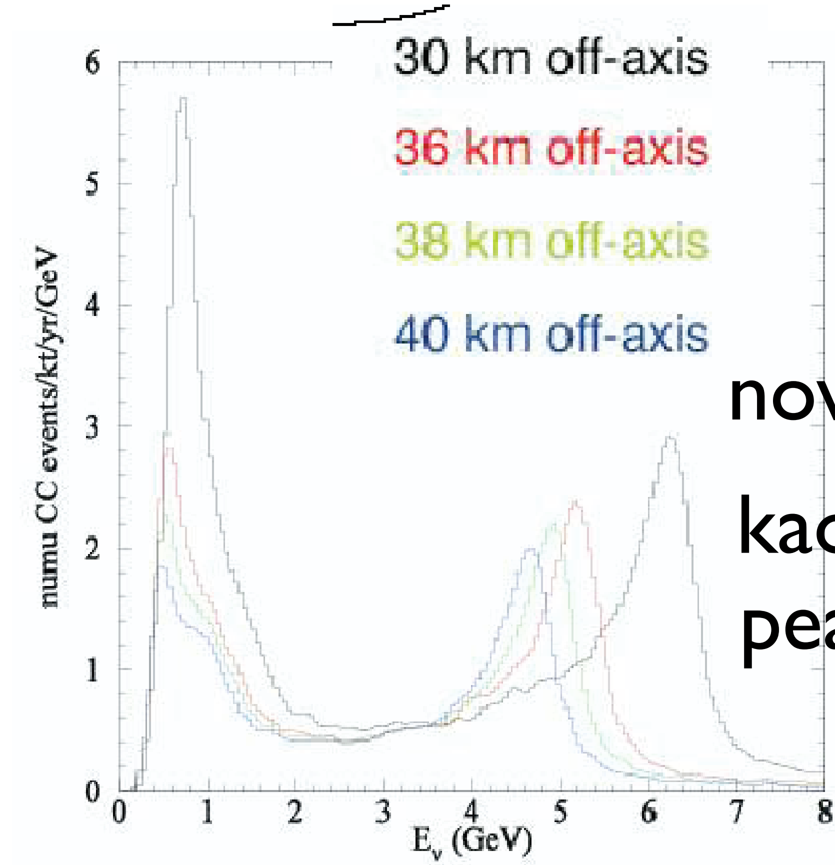
NOVA1 and NOVA2 locations

Super Neutrino Beam to DUSEL Candidate Sites



off axis spectra



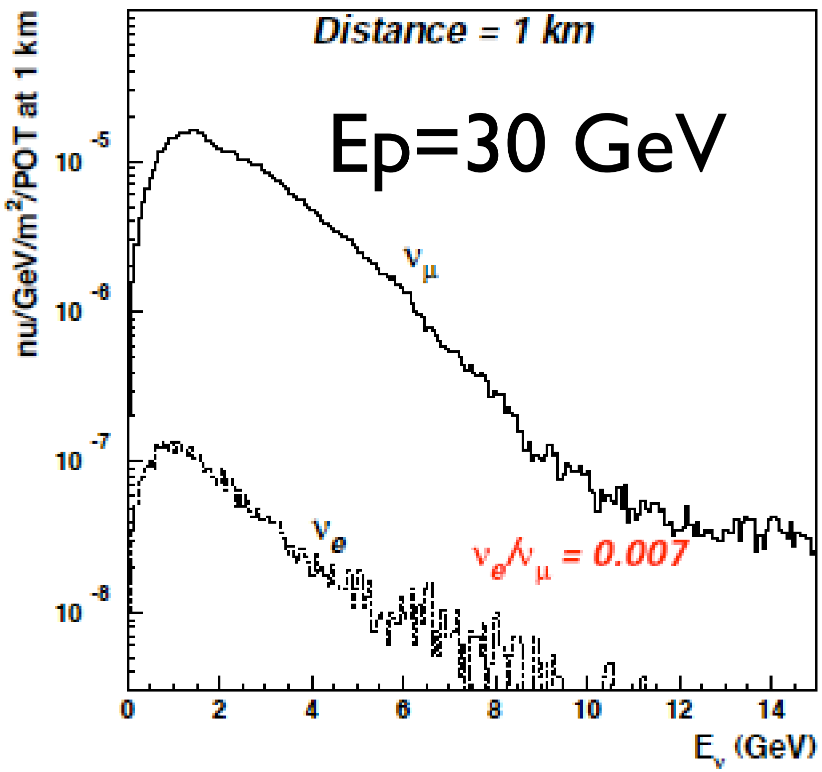


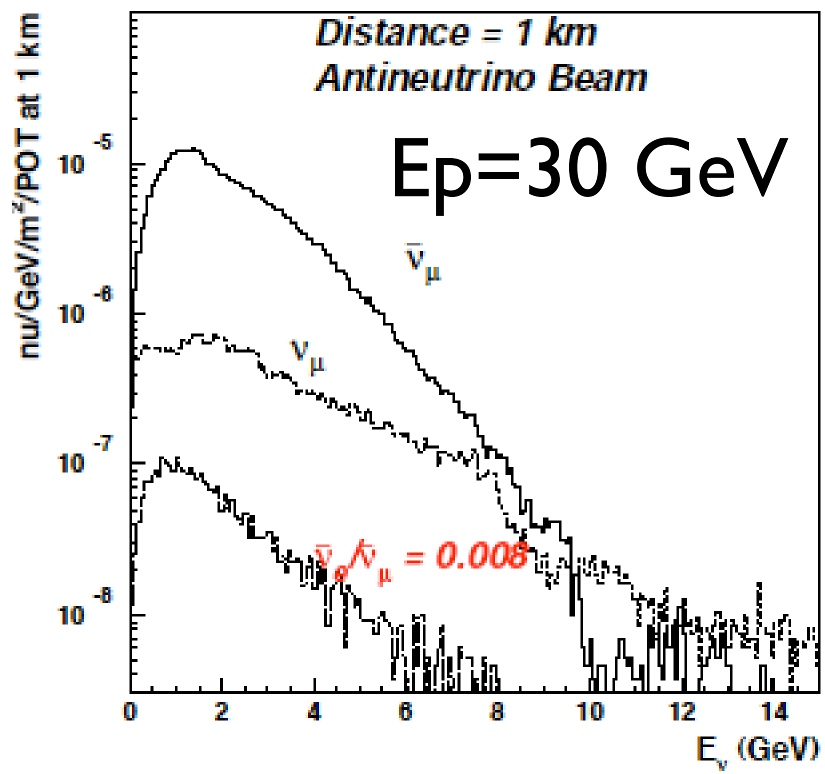
nova-2

kaon peak

- nova-1 event CCrate: ~10000 (30kT*0.65MW*5e7sec)
- nova-II event CCrate: ~1000 (50kT*0.65MW*5e7sec)

wideband spectra





- Low energy wideband 0.5-6 GeV. 200 m decay tunnel.
- FNAL-HS (1300km) nu CC rate: 75000/200kT*1MW*5e7sec
- FNAL-HS (1300 km) anti-nu CC: 25000/200kT*1MW*5e7 sec

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Total exposure

- Assume total exposure for wideband to be 2500kT*MW*(10^7)sec for each polarity.
- Off axis program exposure is more complex.
- nu: 30kT*2MW*6yr+ 80kT*2MW*3yr
- antinu: same

FNAL/BNL study

- Chairs: Hugh Montgomery, Sally Dawson
- First kick-off workshop was on March 6-7
- Very successful ! Very good work reported on physics sensitivity, backgrounds, possible beam from FNAL, etc.
- Study goals and initial work plan sent out.

http://www.fnal.gov/directorate/DirReviews/Neutrino_Wrkshp.html

FUTURE_LONG_BASELINE_LIST@fnal.gov

To get on the list send email to

rameika@fnal.gov

Timescale:

The United States neutrino community is heavily engaged in operation and analysis of its existing program. On the other hand there are active discussions within advisory bodies and the agencies with a view to setting directions for future facilities inside the next year.

It would be desirable to see results of this **U.S. Long Baseline Neutrino Experiment Study** before October 2006, with a preliminary report by July 15, 2006.

Goals of workshop and study

U.S. Long Baseline Neutrino Experiment Study

Compare the neutrino oscillation physics potential of:

1. A broad-band proposal using a either an upgraded beam of around 1 MW from the current Fermilab accelerator complex or a future Fermilab Proton Driver neutrino beam aimed at a DUSEL-based detector. Compare these results with those previously obtained for a high intensity beam from BNL to DUSEL.

2. Off-Axis next generation options using a 1-2 MW neutrino beam from Fermilab and a liquid argon detector at either DUSEL or as a second detector for the Nova experiment.

Considerations of each should include:

i) As a function of θ_{13}, the ability to establish a finite θ_{13}, determine the mass hierarchy, and search for CP violation and, for each measurement, the limiting systematic uncertainties.

ii) The precision with which each of the oscillation parameters can be measured and the ability to therefore discriminate between neutrino mass models.

iii) Experiment Design Concepts including:

Optimum proton beam energy
Optimum geometries
Detector Technology
Cost Guesstimate

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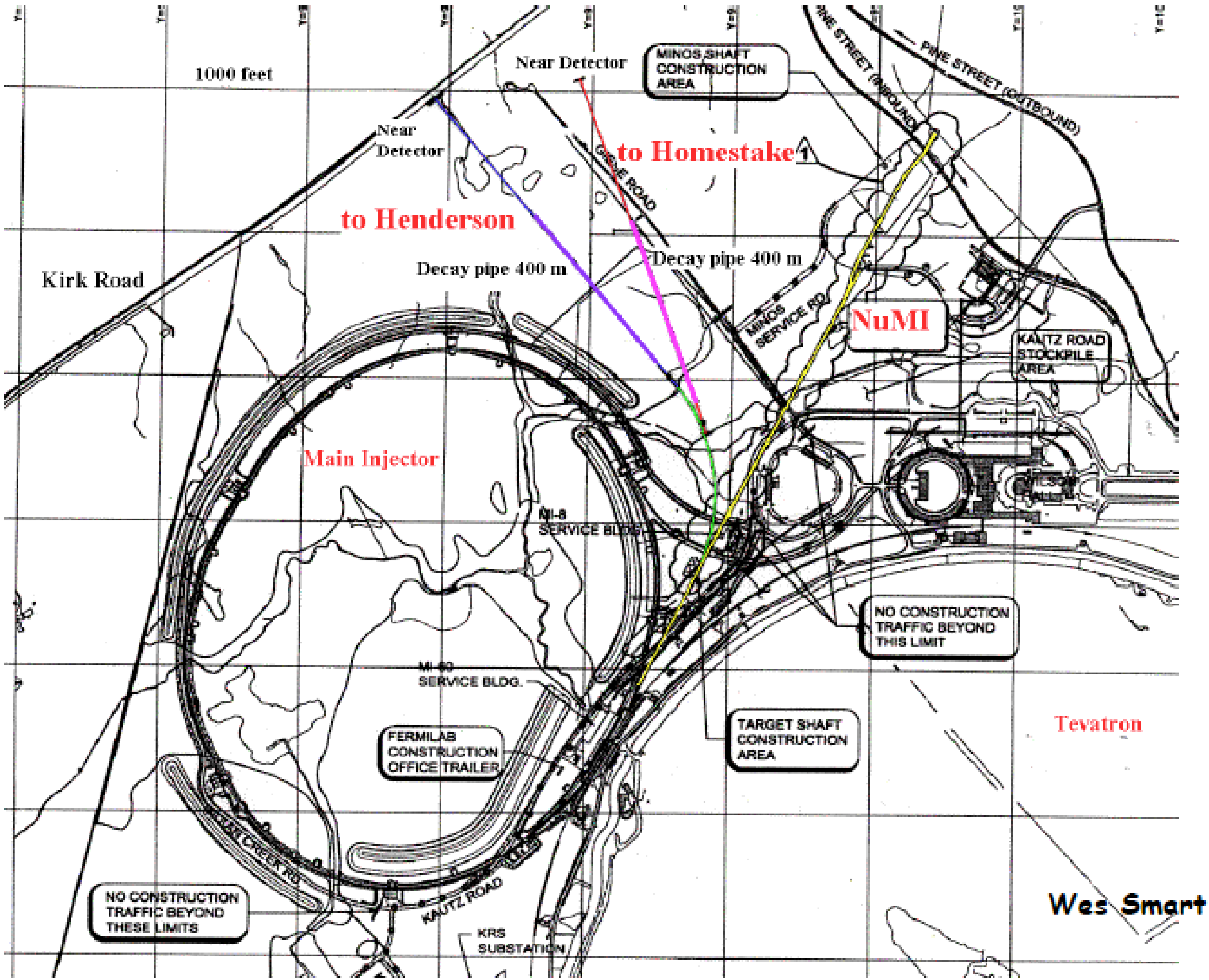
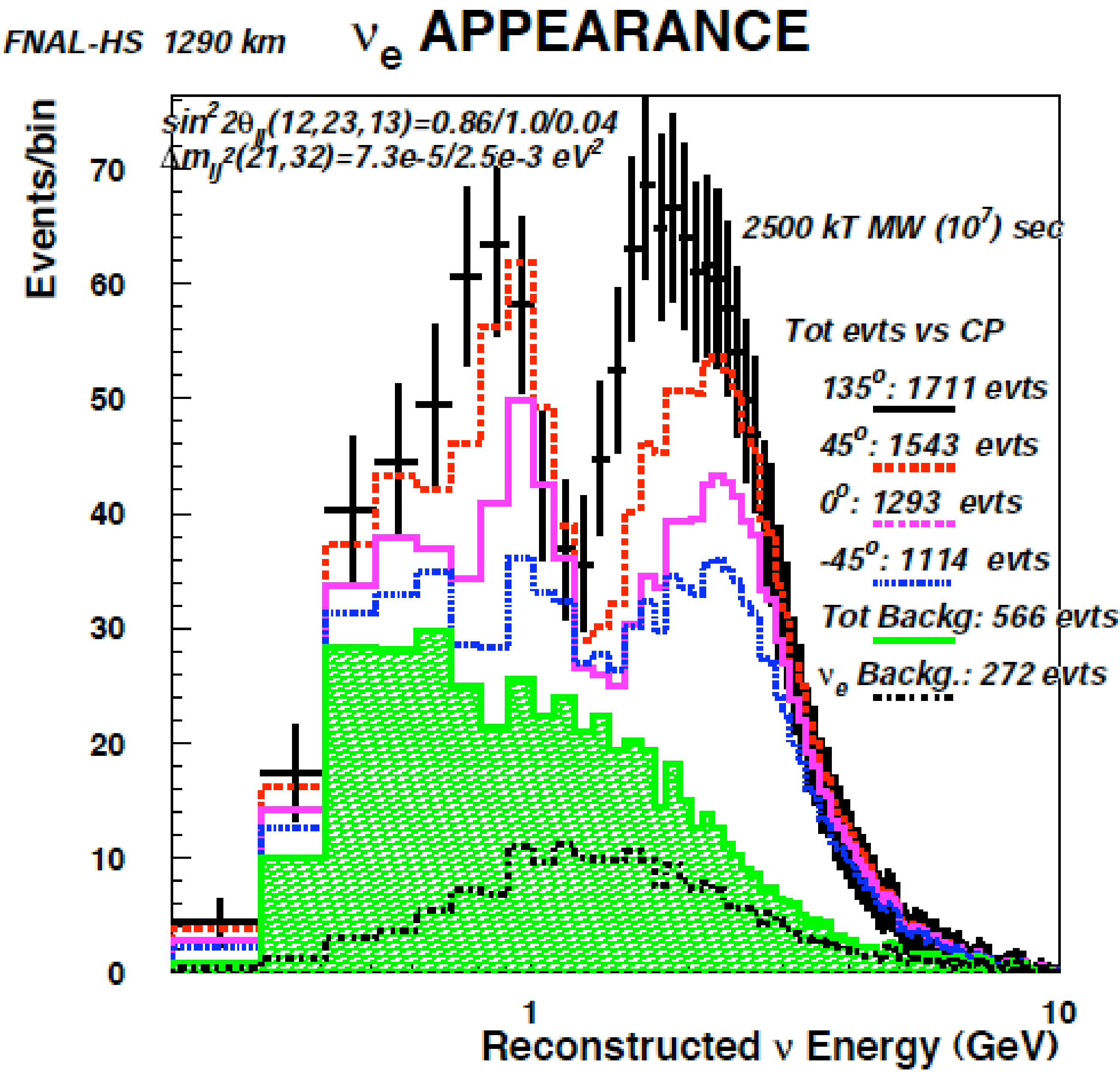
US possibilities for new wideband beam

Source	Proton beam energy	Proton beam power	
FNAL MI (upgrade using recycler)	Ep=8-120GeV	<1 MW X(Ep/120GeV)	A. Marchionni
FNAL MI (with 8GeV LINAC)	Ep=8-120 GeV	2 MW @ any Ep	G. Apollinari
BNL-AGS (upgrade 2.5- 5 Hz)	Ep=28 GeV	1-2 MW	BNL-73210



1000 feet
Near Detector
Near Detector
MINOS SHAFT CONSTRUCTION AREA
PINE STREET (INBOUND)
PINE STREET (OUTBOUND)
to Homestake
to Henderson
GIESE ROAD
Kirk Road
Decay pipe 400 m
Decay pipe 400 m
MINOS SERVICE RD
NuMI
KAUTZ ROAD STOCKPILE AREA
Main Injector
MI-8 SERVICE BLDG.
NO CONSTRUCTION TRAFFIC BEYOND THIS LIMIT
MI-60 SERVICE BLDG.
TARGET SHAFT CONSTRUCTION AREA
Tevatron
FERMILAB CONSTRUCTION OFFICE TRAILER
NO CONSTRUCTION TRAFFIC BEYOND THESE LIMITS
KAUTZ ROAD
KRS SUBSTATION
Wes Smart

ν_e Appearance



Backgrounds

- beam ν_e
- Neutral current events

ν running

- measure $\sin^2 2\theta_{13}$ and δ_{CP}.
- resolve mass hierarchy for $\sin^2 2\theta_{13} > 0.01$
- with $\bar{\nu}$ running $\sin^2 2\theta_{13} > 0.003$ at 90% C

If $\sin^2 2\theta_{13}$ too small δ_{CP} cannot be measured. (See Patrick's curves).

ν_μ Disappearance

Very easy to get this effect
Does not need extensive pattern recognition. Can enhance the second minimum by background subtraction.

Neutrino Running

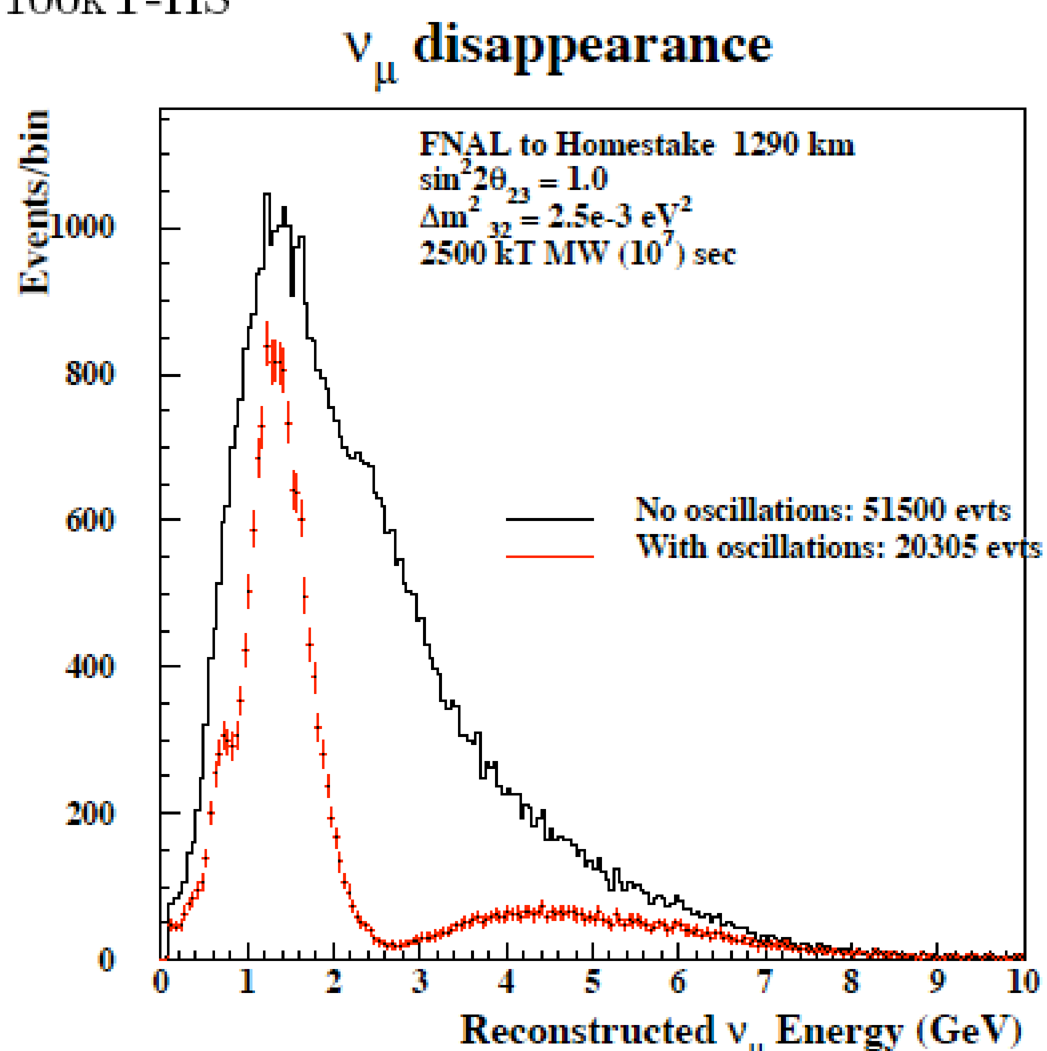
- Total exposure: 2500 kT.MW.(10^7).sec
- 195000 CC evts/6yrs: 2MW-FNAL, 100kT-HS
- Use only clean single muon events.

Measurements

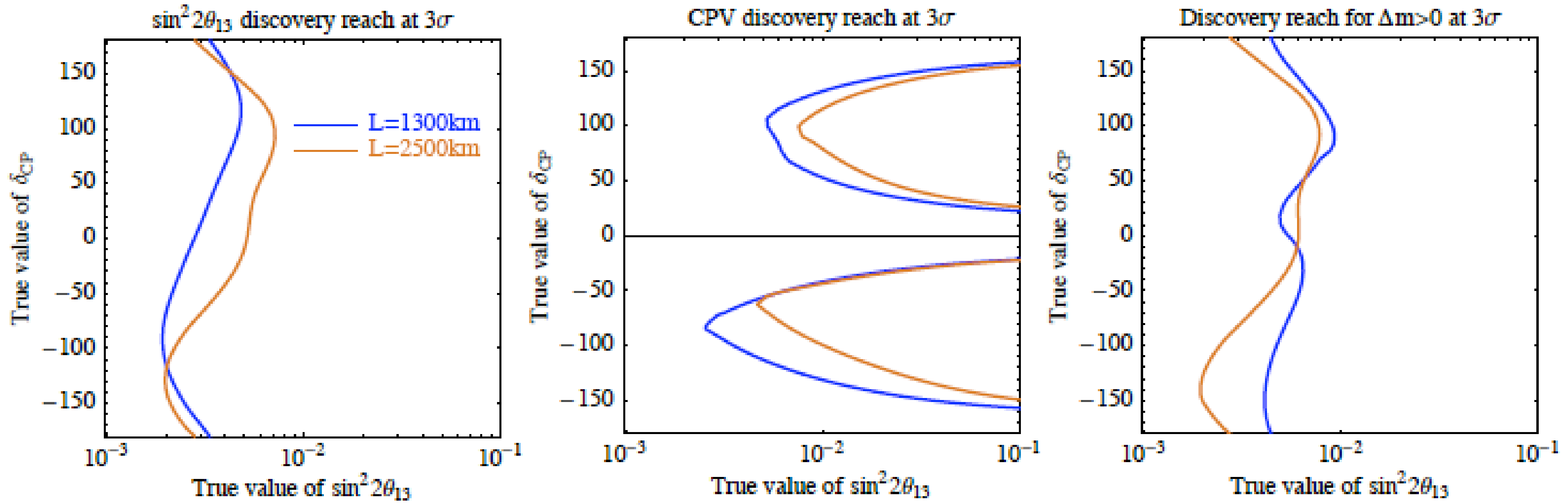
- 1% determination of Δm^2_{32}
- 1% determination of $\sin^2 2\theta_{23}$
- Most likely systematics limited.

$\bar{\nu}$ running

- Need twice the exposure for similar size data set.
- very precise CPT test possible.



Wide band beam

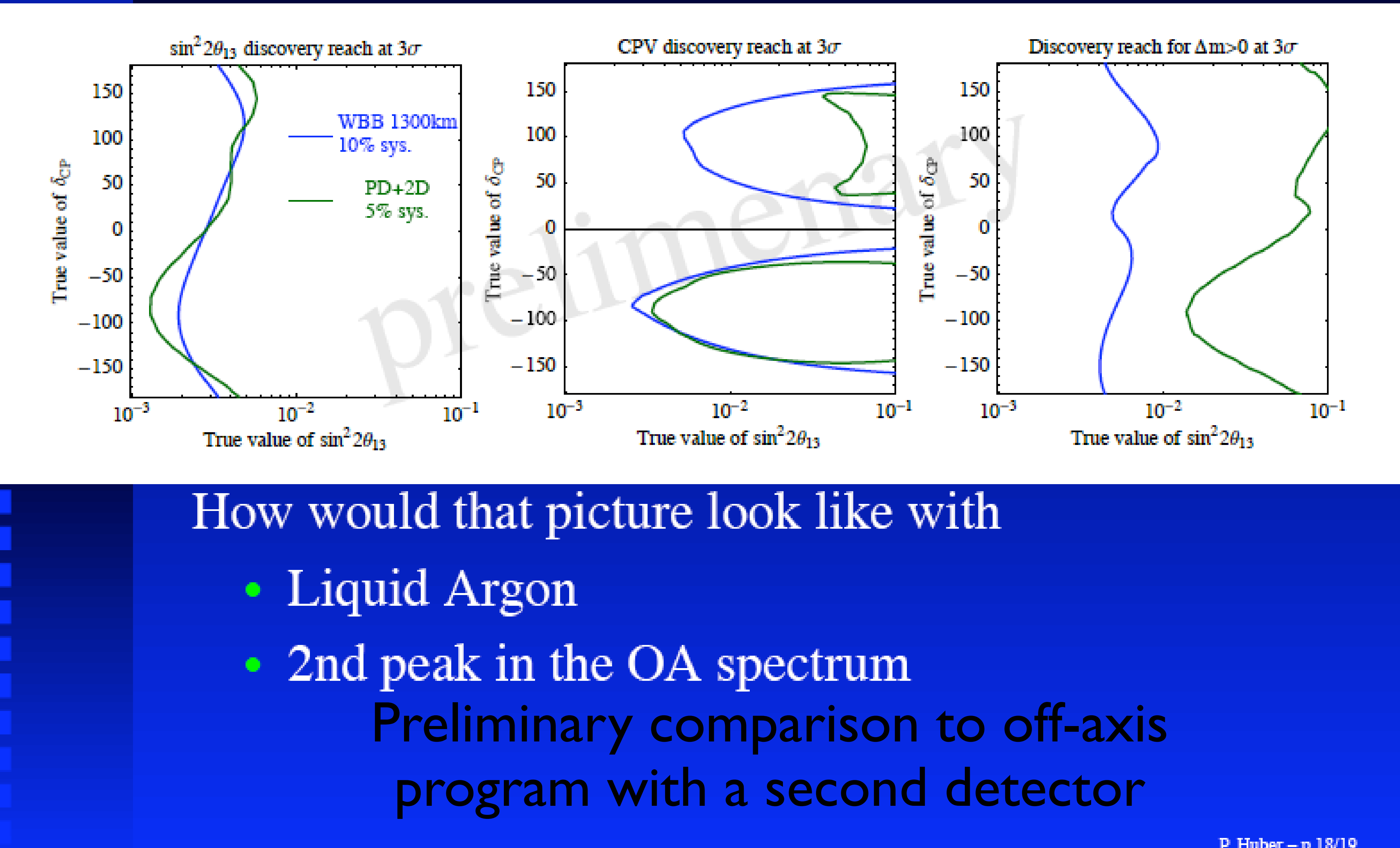


- very good resolution of the mass hierarchy
- no problems due to π-transit for $\sin\delta > 0$
- Baseline choice is not critical

includes anti running, but large fraction of the result is from nu running for normal hierarchy

P. Huber – p.17/19

Summary



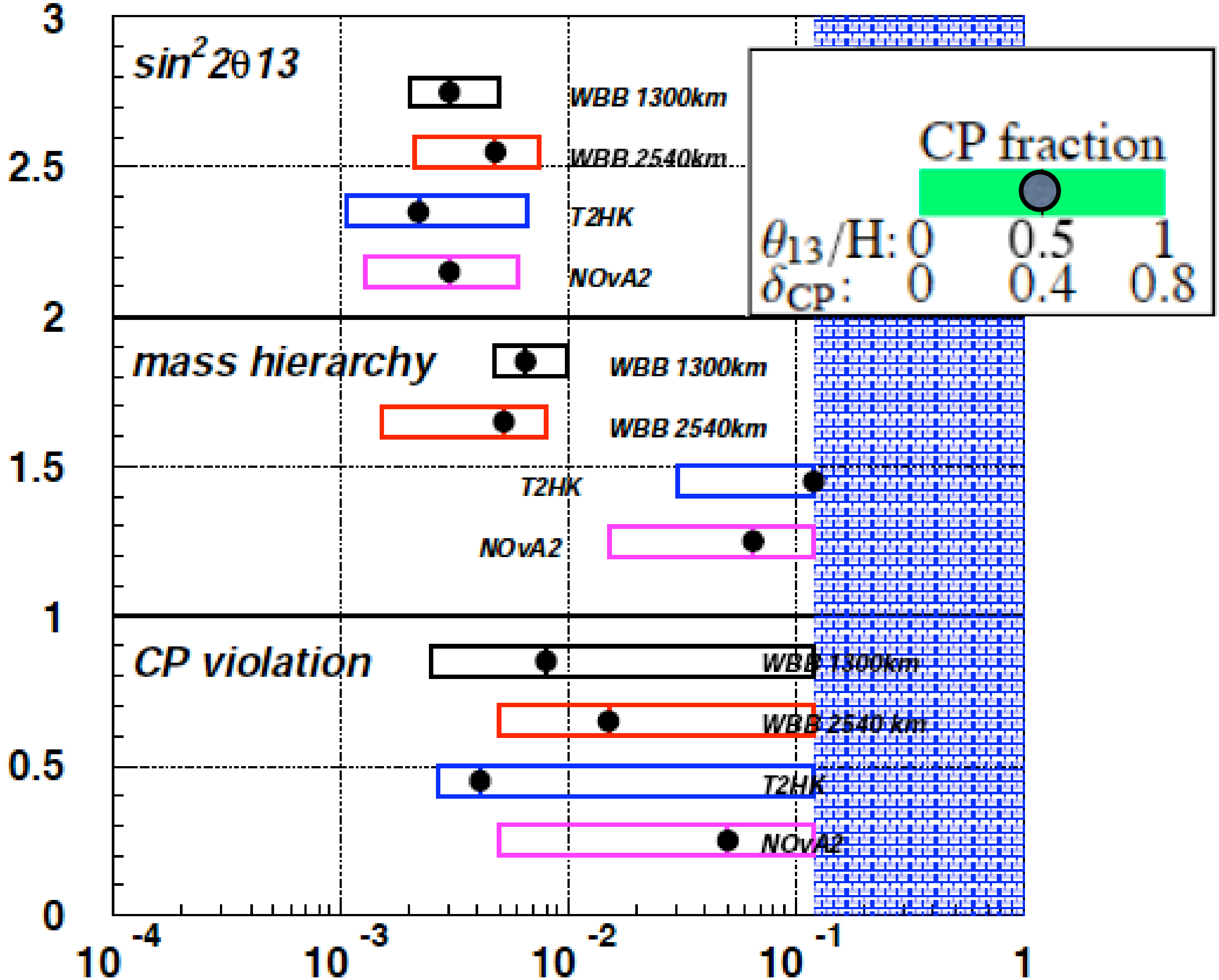
How would that picture look like with

- Liquid Argon
- 2nd peak in the OA spectrum

Preliminary comparison to off-axis program with a second detector

Assumptions

Comparison of 3σ reach



- WBB: nu:200kT*1MW*6yr. antinu: 200kT*1MW*6yr syst: 10% on bck Antinu running is over-constraint for normal hierarchy.
- T2HK: nu: 1000kT*4MW*3yr antinu: 1000kT*4MW*3yr syst: 2% on bck
- NOVA2: nu:30kT*2MW*6yr+ 80kT*2MW*3yr antinu: same*6yr+3yr syst: 5% on bck

Preliminary result out of FNAL workshop

Summary

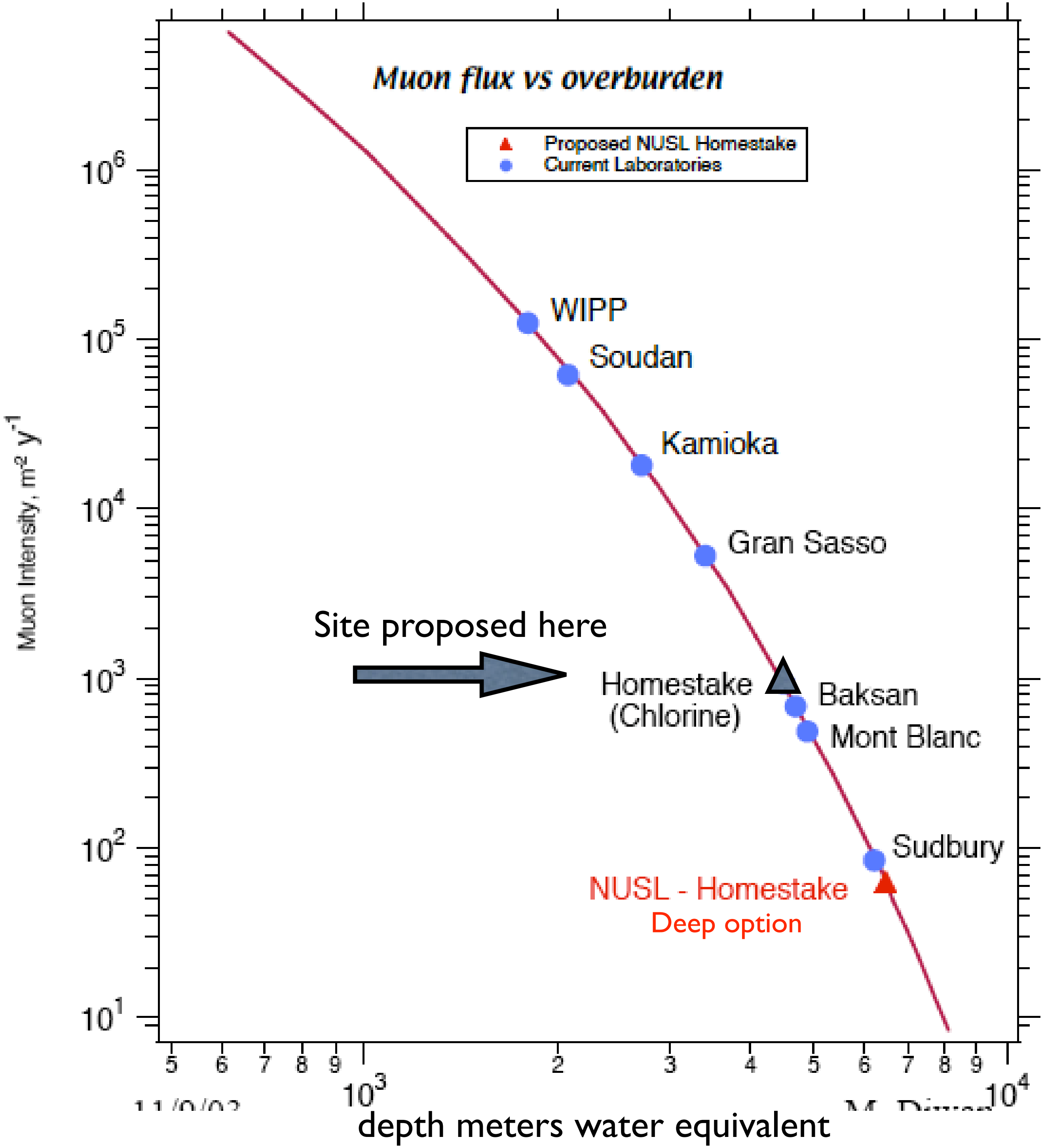
- I reviewed the physics considerations for a long baseline and very long baseline program.
- A new MW class proton machine in the US remains well-motivated.
- The two US possibilities are a two detector off axis program or a DUSEL based very long baseline program.
- A new joint laboratory (FNAL/BNL)study has been launched to evaluate these.
- The study will report to NUSAG this year.

4850ft: 100kT ~3M mu/yr

with rate of 1 mu/10 sec => may not need veto-counter

The Beam neutrinos will be obvious with a rate of 100-200/day in 10 mus spills.

No pattern recognition beyond time cut is needed.



Exploring the possibility of neutrino beams towards a DUSEL site

W. Smart

	Latitude	Longitude	Vertical angle from FNAL (deg)	Distance from FNAL (km)
Homestake	44.35	-103.77	-5.84	1289
Henderson	39.76	-105.84	-6.66	1495

- Use of the present extraction out of the Main Injector into the NuMI line
- Construction of an additional tunnel, in the proximity of the Lower Hobbit door in the NuMI line, in order to transport the proton beam to the west direction
- Radius of curvature of this line same as the Main Injector, adequate for up to 120 GeV/c proton beam with conventional magnets
- Assumptions:
  - **a target hall length of ~45 m (same as NuMI for this first layout, probably shorter)**
  - **decay pipe of 400 m (adequate for a low energy beam), we would gain in neutrino flux by increasing the decay pipe radius (> 1 m)**
  - **distance of ~300 m from the end of the decay pipe to a Near Detector (same as NuMI).**

Open issues on detector

- Depth and veto counter - has cost, schedule and physics implications. Perhaps only the first module is built without veto-counter for a fast start.
- Fiducial volume.   If SK cut good enough => 75 kT.
- PMT coverage: 20 % adequate from SK experience. 40% if very low threshold is needed.
- PMT size: 13 inch versus 20 inch. Greater number of pixels will give better pattern recognition.
- Size of detector: very difficult to increase span. If made bigger has cost and schedule implications. 50 meter span seems adequate to contain beam events.

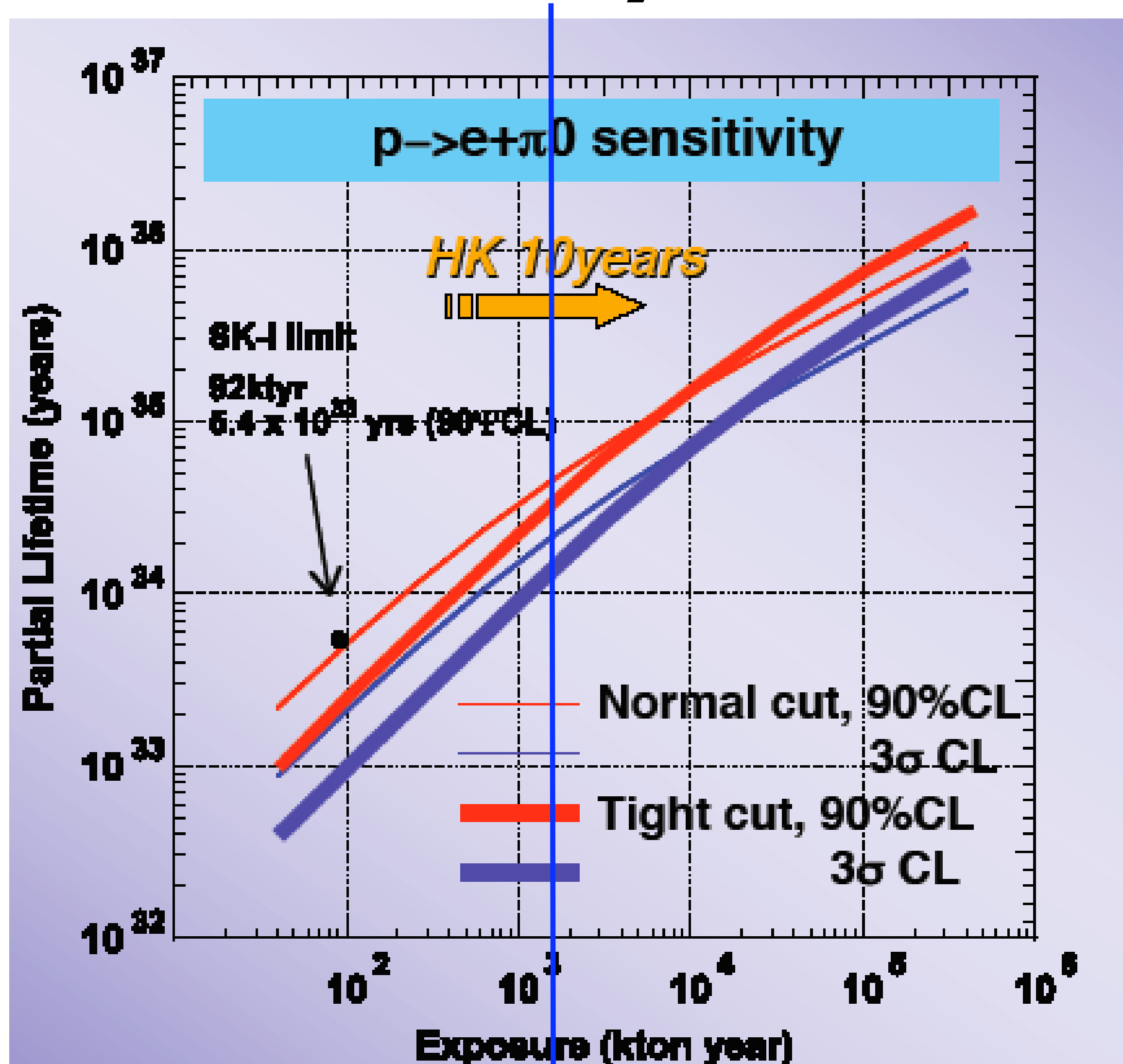
Open issues on beam

- What is the correct proton energy and power level from FNAL
- What is the cost of a new beam
- To get intensity at low energies must have ~4 meters diameter tunnel. I have length of 200 meters to get the spectra in this talk.
- How should we tailor the spectrum for maximum signal/noise ?
- If tunnel is wide WE CAN ALWAYS RUN OFFAXIS by moving and tilting the horn/target. (upto 1 deg.)
- What is the time sequence ? Proposal on next slide.

Nucleon decay

- Large body of work by HyperK, and UNO.
- background levels for the positron+Pion mode
  - 3.6/MTon-yr (normal)
  - 0.15/MTon-yr (tight)

LMD-I and II (200kT) will hit backg. in ~1.5yrs. It could be important to perform this first step before building bigger. Sensitivity on K-nu mode is about ~8x10^33 yr



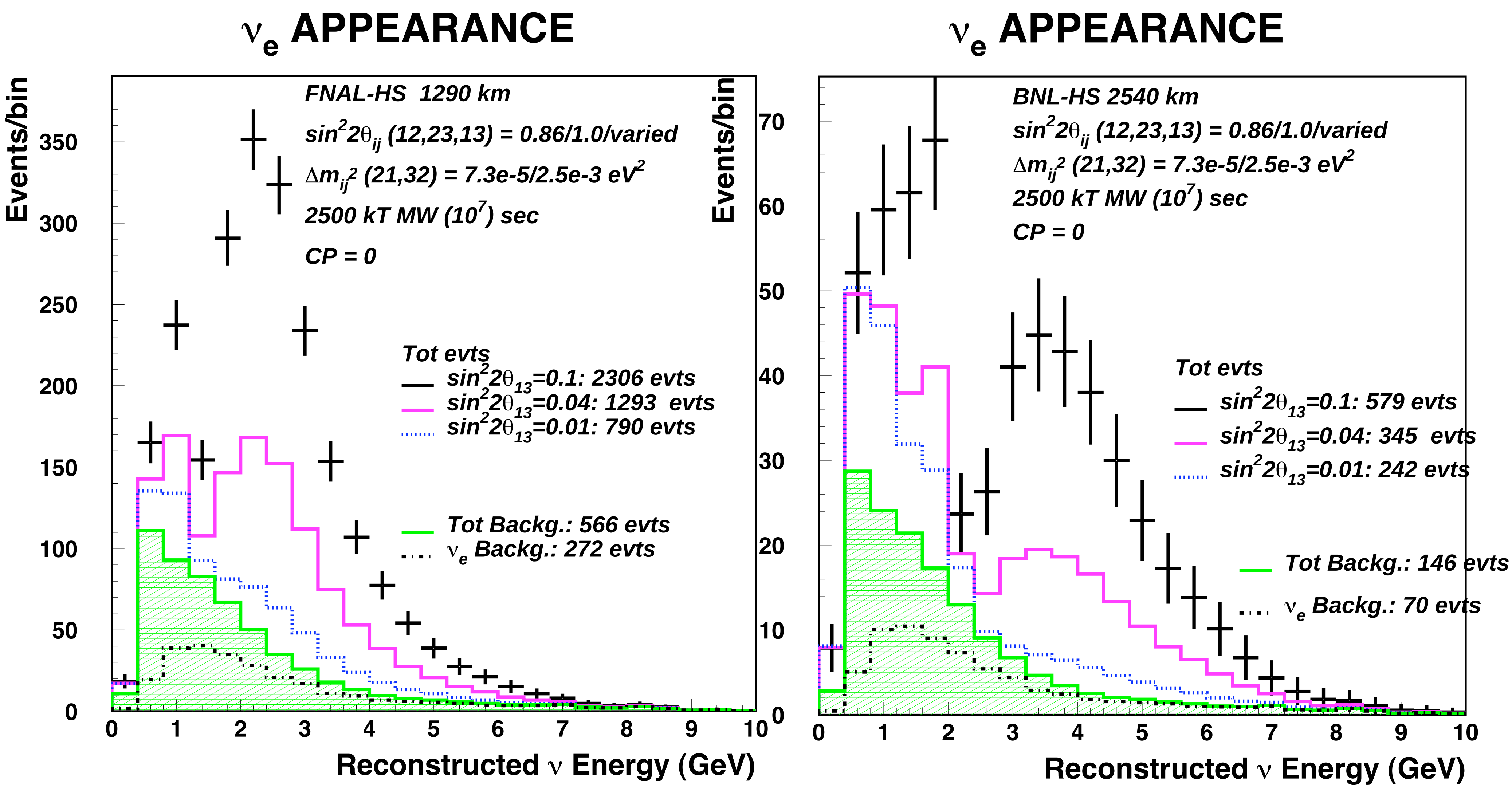
Ref: Shiozawa (NNN05)

150kTX10yrs 5X10^34 yrs

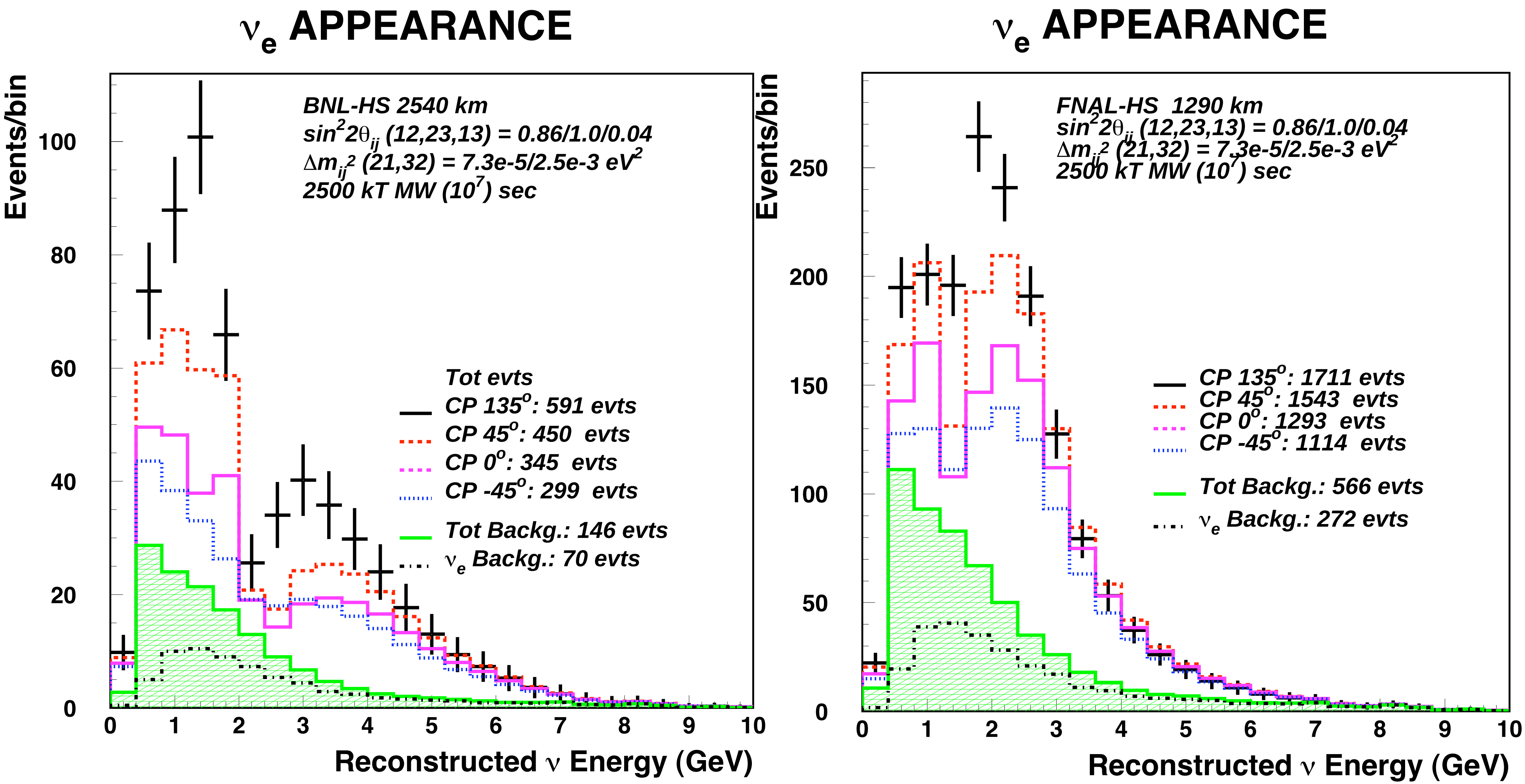
Astrophysical Neutrinos
Event rates. LMD-I&II(200kT), 5 yrs

- Atmospheric Nus: ~20000 muon, ~10000 electrons. (Ref: Kajita nnn05)
- Solar Nus: >120000 elastic scattering E>5MeV (including Osc.) (Ref: uno)
- Galactic Supernova: ~60000/10 sec in all channels. (~2000 elastic events). (Ref: uno)
- Relic Supernova: (ref: Ando nnn05)
  - flux: ~5 (1.1) /cm2/sec Enu>10 (19) MeV
  - rate: 150 (70) events over backg ~200 !

Need analysis with these numbers



ν_e APPEARANCE
FNAL-HS 1290 km
$sin^2 2\theta_{ij}$ (12,23,13) = 0.86/1.0/varied
Δm_{ij}^2 (21,32) = 7.3e-5/2.5e-3 eV^2
2500 kT MW (10^7) sec
CP = 0
Tot evts
$sin^2 2\theta_{13}$=0.1: 2306 evts
$sin^2 2\theta_{13}$=0.04: 1293 evts
$sin^2 2\theta_{13}$=0.01: 790 evts
Tot Backg.: 566 evts
ν_e Backg.: 272 evts
Events/bin
Reconstructed ν Energy (GeV)
ν_e APPEARANCE
BNL-HS 2540 km
$sin^2 2\theta_{ij}$ (12,23,13) = 0.86/1.0/varied
Δm_{ij}^2 (21,32) = 7.3e-5/2.5e-3 eV^2
2500 kT MW (10^7) sec
CP = 0
Tot evts
$sin^2 2\theta_{13}$=0.1: 579 evts
$sin^2 2\theta_{13}$=0.04: 345 evts
$sin^2 2\theta_{13}$=0.01: 242 evts
Tot Backg.: 146 evts
ν_e Backg.: 70 evts
Events/bin
Reconstructed ν Energy (GeV)



Comparison to 1290 km to 2540 km